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Multi objective optimization of hot machining of 15-5PH stainless steel using grey relation analysis

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Abstract

In this paper an experimental investigation was carried out to optimize the performance characteristics (surface roughness and Metal removal rate) simultaneously in hot machining process. The experiments were conducted on 15-5PH stainless steel using K313 carbide tool based on Taguchi L_{27} orthogonal array design. The work-piece material was heated using oxy-acetylene gas flame which is the cost effective method compare to other heating technique used in hot machining process. Analysis of variance is performed to get the contribution of each parameter on the performance characteristics and it was observed that cutting speed is most significantly affect the performance characteristics compare to feed, depth of cut and temperature. The optimal set of process parameters were found to be cutting speed at 31 m/min, feed rate at 0.4mm/rev, depth of cut at 0.4 mm and workpiece temperature at 400^0C to maximize material removal rate and minimize surface roughness.

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Keywords: 15-5PH stainless steel, Hot machining, surface roughness, MRR, S/N ratio, grey relational analysis.

1. Introduction:

Precipitation hardenable martensitic stainless steel 15-5PH has remarkable advantages in aerospace industries particularly in (actuator parts for modern aircrafts), nuclear industries, chemical, petrochemical, gears, pumps, food processing, paper and general metalworking industries (Alexander et al.,2013). These materials exhibit excellent mechanical properties, high strength and hardness, good corrosive resistance, weldability, low distortion. Precipitate hardened stainless steels exhibit high strengths at temperatures up to 315^0C like other martensitic stainless steels (Ashok kumar et al., 2013) .

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The hardness of 15-5PH stainless steel is 40 HRC and it is also one of the hard to cut materials. This paper mainly focuses on the material removal rate and surface finish generated by hot turning of the 15-5PH stainless steel.

Now a day's industries are facing so many problems in machining hard to cut materials like alloys of molybdenum, titanium, nickel, tungsten, tantalum, ceramics (Uehara et al., 1986). Conventional machining of these materials have problems like low speeds, feeds, poor surface finish, high tool wear, less tool life low production, in another aspect unconventional machining is often employed for machining of these materials. But, the unconventional machining setup involved a high capital cost and offers a low material removal rate. To overcome these problems hot machining is one of the most potential techniques developed to machine hard to cut materials.

In hot machining a part or whole workpiece is heated before or during machining (Lei et al., 2001). Heating of the material makes high hardness of the material become soft, resulting in improved machinability, high production rate, low power consumption from all these advantages hot machining is extremely used full to machine hard to cut materials like ceramics (Ozler et al., 2001). Many researchers have used different heating techniques like laser heating, plasma heating, induction heating, electrical heating and they were proved that these heating techniques are expensive. Several researchers reported that there is an improvement in both surface finish and tool life in hot machining (Akasawa et al 1987, Ueharaet al 1986, Hinds et al 1980, Raghuram et al 1979, Chen et al 1973, Pal et al 1969). In hot machining it was observed that the cutting mechanism of the ceramics changes from brittle fracture type to plastic deformation type by (Ueharaet al.,1986). Hinds et al., (1980) suggested that the shape of the heat source and positioning of the torch also affects overall efficiency. Materials of different hardness's were machined using different grades of carbide tools, over a range of cutting speeds and heating current. Chen et al., (1973) and Uehara et al, (1983) improved the cutting performance by the using coated carbide tools in electric hot machining, suggesting new possibilities in the field of the machining of low machinability metals**.** Raghuram et al., (1979) tool life is observed to increase if a magnetic field is applied during machining . The cooling method of the cutting tool is very effective for reducing the tool wear in the hot machining process (Akasawa et al., 1987). In plasma hot machining cutting forces is decreasing by machining high hardness materials (Kitagawa et al., 1990).

S.K Thandra et al. (2010) have compared hot machining over conventional machine it was found that cutting forces, surface roughness, flank wear by about 34%. Spindle power is reduced up to 25% in hot machining of hardened steels has shown experimentally (Madhavulu et al.,1994). Hot machine is mainly suitable for turning process but some of the researchers used in shaping, milling, drilling forging (Pal et al., (1971), Lopez et al., (2004), Uehara et al., (1983)) from the extensive research it was found that Oxy acetylene gas flame is inexpensive compared to all techniques.

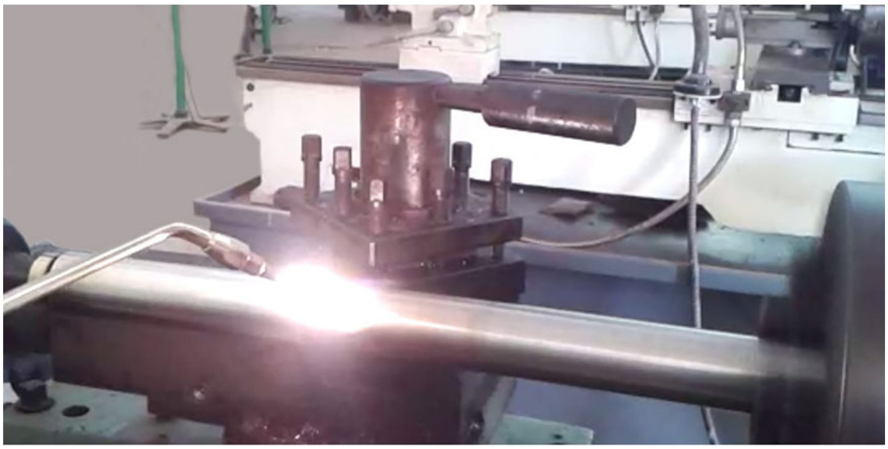

Fig 1 Hot machining setup

2. Experimental procedure

The experiments were performed on the lathe with different feeds, speeds, depth of cut and workpiece temperature is summarized in Table 1. K313 carbide as a tool and 15-5PH martensitic stainless steel with 32mm diameter as workpiece used in these experiments. The chemical composition of 15-5PH stainless steel with 40 HRC is shown in Table 2. Experiments are conducted by using the oxyacetylene heating setup for heat the workpiece. Oxyacetylene heating is one of the best choices for hot machining because it requires low equipment cost the heat transfer to the workpiece is very low. Metallurgical damage of the workpiece is very low. Hot machining setup is shown in Fig.1.The temperature of the workpiece is measured by using K-type thermocouple. The surface roughness of the workpiece are measured by Mitutoyo surf test and the cut off length is 0.8mm and the number of samplings was taken as three were used in the measurements. The metal removal rate was calculated by using the formula

$$MRR = V_c f_s d_p \qquad (1)$$

Where MRR is the volume of the material removal rate (cm^3/min) V_c is the cutting speed (m/min), f_s is the feed rate (mm/rev), and d_p is the depth of cut (mm)

To identify the optimal machining parameters from the multi performance characteristics, The orthogonal array with Grey Relational analysis was used. The full factorial design experiment would require 3^4 = 81 experimental runs, to perform all the experiments it requires more effort and experimental cost. For this Taguchi method is a power full tool used for parametric design were used. The total degree of freedom organized with four parameters was equal to 20. Therefore, orthogonal array having a degree of freedom >20 should be selected. A standard L_{27} orthogonal array is used because it has 26 degrees of freedom which is greater than 20 degrees of freedom. Four hot machining parameters were chosen as control factors, and each parameter was designed to have three levels, denoted 1, 2, and 3. The obtained values of surface roughness and metal removal rate are presented in Table 3.

Table 1 Parameters and their levels of cutting experiments

Cutting parameters	Levels			Units
	I	II	III	
Cutting speed	31	77	120	m/min
Feed rate	0.2	0.3	0.4	mm/rev
Depth of cut	0.4	0.8	1	mm
W/P Temperature	200	400	600	ºC

Table 2 Chemical composition of 15-5PH stainless steel

Element	C	Mn	P	S	Si	Cr	Ni	Cu	C&Ta
%	0.07	1.00	0.040	0.030	1.00	14-15.50	3.5-5.5	2.5-4.5	0.15-0.45

3. Grey relational analysis

Taguchi method is one of the best techniques for design and analyses the experiments to improve the product quality, it can simplify the optimization of process parameters for multi performance characteristics. In this method loss function is used to measure the performance characteristics deviated from the desired value (Bundell T.,1998). In the grey relation analysis, grey relation coefficient is calculated for different process characteristics and average of these grey relation coefficient gives the grey relation grade. Statistical ANOVA analysis is performed to find out the significant process parameters, with the grey relation analysis and the statistical analysis of variance, the optimum combination of process parameters can be predicted. Then finally the conformation test is performed to verify the optimal process parameters obtained from the design (Aravindan et al.,2008).

3.1 S/N ratio to compute hot machining characteristics

Hot machining of 15-5PH stainless steel, the surface roughness of the machined parts has been considered as smaller the better, whereas the metal removal rate, and tool life is considered as higher the better. These considerations has been taken for good quality characteristics of interest.

For the present study S/N ratio for metal removal rate is calculated using the formula.

$$\eta = -10 log \frac{1}{n} \sum (1 / y_i^2) \quad (2)$$

S/N ratio for surface roughness of the machined parts is calculated using the formula Patel Pulak et al (2010)

$$\eta = -10 \, log \frac{1}{n} \sum (y_i^2) \quad (3)$$

The experimental results of surface roughness (Ra), metal removal rate, and S/N ratios are shown in Table 3.

Table 3 Experimental results of hot machining

S.No	Speed m/min	Feed Mm/rev	Depth of cut mm	Temp ^{0}C	Ra µm	MRR Cm^3/min	S/N Ratio Ra	S/N ratio MRR
1	31.00	0.20	0.40	200.00	1.45	2.48	3.23	-7.89
2	31.00	0.20	0.80	400.00	1.42	4.96	3.05	-13.91
3	31.00	0.20	1.00	600.00	1.53	6.20	3.69	-15.85
4	31.00	0.30	0.40	400.00	2.58	3.72	8.23	-11.41
5	31.00	0.30	0.80	600.00	3.02	7.44	9.60	-17.43
6	31.00	0.30	1.00	200.00	2.91	9.30	9.28	-19.37
7	31.00	0.40	0.40	600.00	4.84	4.96	13.70	-13.91
8	31.00	0.40	0.80	200.00	4.27	9.92	12.61	-19.93
9	31.00	0.40	1.00	400.00	4.64	12.40	13.33	-21.87
10	77.00	0.20	0.40	200.00	2.22	6.16	6.93	-15.79
11	77.00	0.20	0.80	400.00	2.24	12.32	7.00	-21.81
12	77.00	0.20	1.00	600.00	2.27	15.40	7.12	-23.75
13	77.00	0.30	0.40	400.00	3.30	9.24	10.37	-19.31
14	77.00	0.30	0.80	600.00	3.22	18.48	10.16	-25.33
15	77.00	0.30	1.00	200.00	3.40	23.10	10.63	-27.27
16	77.00	0.40	0.40	600.00	4.61	12.32	13.27	-21.81
17	77.00	0.40	0.80	200.00	4.67	24.64	13.39	-27.83
18	77.00	0.40	1.00	400.00	4.87	30.80	13.75	-29.77
19	120.00	0.20	0.40	200.00	1.47	9.60	3.35	-19.65
20	120.00	0.20	0.80	400.00	1.71	19.20	4.66	-25.67
21	120.00	0.20	1.00	600.00	1.75	24.00	4.86	-27.60
22	120.00	0.30	0.40	400.00	3.38	14.40	10.58	-23.17
23	120.00	0.30	0.80	600.00	2.86	28.80	9.13	-29.19
24	120.00	0.30	1.00	200.00	2.40	36.00	7.60	-31.13
25	120.00	0.40	0.40	600.00	2.87	19.20	9.16	-25.67
26	120.00	0.40	0.80	200.00	3.40	38.40	10.63	-31.69
27	120.00	0.40	1.00	400.00	2.86	48.00	9.13	-33.62

3.2 S/N Ratio for grey relation analysis

In the grey relation analysis, the original experimental data are normalized to reduce the range among the designated performance characteristics. This process is called data pre-processing. and a liner normalization of the s/n ratio is performed (Deng.,1989). When the range of optimal value of a quality characteristic is too large then sum factors are to be ignored to normalize the original experimental data and this is called normalized S/n ratio. So the normalized S/N ratio x_{ij} for the i^{th} performance characteristic in the j^{th} experiment can be performed in the following formula

$$x_{ij}^* = \frac{\eta_{ij} - \min{}_j \eta_{ij}}{\max \eta_{ij} - \min{}_j \eta_{ij}} \quad (4)$$

Where x_{ij} is the sequence after data processing, η_{ij} the original sequence of the S/N ratio (where i=1,2,3…m, j=1,2,3…n), max η_{ij} the largest value of η_{ij} , and min η_{ij} the smallest value of η_{ij} .

Table 4 shows the normalized S/N ratio for surface roughness and metal removal rate. Actually the normalized S/N ratio gives the better performance and the ideal normalized S/N ratio is equal to 1. The relationship between the ideal normalized S/N ratio and actual normalized S/N ratio is called grey relational coefficient. The grey relational coefficient which can be calculated using the following formula ξ_{ij} for the ith performance characteristic in the jth experiment can be calculated using the following formula

Table 4 Normalized S/N Ratio and Grey Relation grade and its order

S.No	Normalized S/N Ra	Normalized S/N MRR	Grey relation coefficient Ra	grey relation coefficient MRR	Grey grade	Order
1	0.02	1.00	0.34	1.00	0.668	6
2	0.00	0.77	0.33	0.68	0.507	16
3	0.06	0.69	0.35	0.62	0.483	18
4	0.48	0.86	0.49	0.79	0.639	8
5	0.61	0.63	0.56	0.57	0.569	10
6	0.58	0.55	0.54	0.53	0.537	12
7	1.00	0.77	0.99	0.68	0.836	1
8	0.89	0.53	0.82	0.52	0.670	5
9	0.96	0.46	0.93	0.48	0.703	2
10	0.36	0.69	0.44	0.62	0.530	13
11	0.37	0.46	0.44	0.48	0.461	20
12	0.38	0.38	0.45	0.45	0.447	22
13	0.68	0.56	0.61	0.53	0.571	9
14	0.66	0.32	0.60	0.42	0.511	15
15	0.71	0.25	0.63	0.40	0.515	14
16	0.96	0.46	0.92	0.48	0.699	3
17	0.97	0.22	0.94	0.39	0.664	7
18	1.00	0.15	1.00	0.37	0.685	4
19	0.03	0.54	0.34	0.52	0.431	24
20	0.15	0.31	0.37	0.42	0.395	26
21	0.17	0.23	0.38	0.39	0.385	27
22	0.70	0.41	0.63	0.46	0.542	11
23	0.57	0.17	0.54	0.38	0.457	21
24	0.43	0.10	0.47	0.36	0.411	25
25	0.57	0.31	0.54	0.42	0.479	19
26	0.71	0.08	0.63	0.35	0.491	17
27	0.57	0.00	0.54	0.33	0.435	23

$$\xi_{ij} = \frac{\min_i \min_j |x_i^{*} - x_{ij}| + \zeta \max_i \max_j |x_i^{*} - x_{ij}|}{|x_i^{*} - x_{ij}| + \zeta \max_i \max_j |x_i^{*} - x_{ij}|} \quad (5)$$

where x_i^{*} is the ideal normalized S/N ratio for the ith performance characteristic and ζ the distinguishing coefficient which is in the range of $0 \leq \zeta \leq 1$.

Later a weighing method is used to combine the grey relational coefficient of each experiment into the grey relational grade. The overall calculation of the multiple performance characteristics is based on the grey relation grade, i.e,

$$\gamma_j = -\frac{1}{m}\sum_{i=1}^{m} \omega_i \xi_{ij} \quad (6)$$

If $\omega_1 = \omega_2 = \omega_3 = 1$,then γ_j is grey relational grade for jth experiment ω_i is the weighing factor for ith performance characteristics and m is the number of performance characteristics, Table 4 shows the grey relational grade for each experiment using L_{27} orthogonal array. An ideal grey relation grade shows that the corresponding S/N ratio is closer to the normalized S/N ratio. As shown in the Table 4 experiment 7 has the ideal multiple performance characteristic among 27 experiments it also has the best grey relational grade. Therefore optimization of typical multiple performance characteristics can be transposed in to the optimization of a single grey relational grade.

As the orthogonal experimental design is used, the effects of hot machining process parameters on the grey relational grade at different levels are independent. The average of grey relational grade at each level of the hot machining process parameters are given in Table 5. In addition to that the total mean of the grey relational grade for all the 27 experiments is evaluated and shown in Table 5. Fig.2 indicates the hot machining parameters at each level on the grey grade. The better the multiple performance characteristic provides the highest grey relational grade To determine the optimal combination of the hot machining process parameters at each levels more accurately by the relative importance among the hot machining process parameters for the multiple performance characteristic (Hsiao et al.,2010).

Table5 Response table for grey relation grade

Symbol	Grey relational grade			
	Process parameters	Level 1	Level 2	Level 3
A	Cutting speed	0.6235	0.5649	0.4474
B	Feed rate	0.4787	0.5280	0.6292
C	Depth of cut	0.5995	0.5251	0.5112
D	Workpiece temperature	0.5464	0.5488	0.5406

3.3 Results and discussion

ANOVA analysis was carried out using the statistical software MINITAB 16. ANOVA technique is a standard statistical technique which is performed to determine the experimental results of input parameters on out response variables. This technique is used to identify the performance of a combined group of parameters to investigate the total variation is significant. In ANOVA the total sum of squares is calculated using formula.

$$`\, ss_T = \sum (n_i - m)^2 \tag{7}$$

Where m is the overall mean of the S/N ratio.

The total sum of squared deviations ,SS_T is divided in to two sources:

$$ss_T = \sum_{i=1}^{n_p} SS_j + SS_e \tag{8}$$

Where SS_j is the sum of squared deviations for each design parameter and is given by

$$ss_j = \sum_{i=1}^{l} (n_{ij} - m)^2 \tag{9}$$

Where n_p is the number of significant parameters and l the number of levels of each parameter. SS_e is the sum of squared error without or with pooled factor, which is the sum of squares corresponds to the insignificant factors. By dividing sum of squares with degrees of freedom we get the Mean square (MS_j) or error (MS_e). Percentage contribution (ρ) of each of the parameters is given by the following equation (Raghunath et al.,2007, Lua HS et al .,2009,Pan et al., 2007).

$$\rho_j = \frac{SS_j}{SS_T} \tag{10}$$

ANOVA analysis is applied to investigate which hot machining process parameters significantly affects the performance characteristic. Table 6 shows the ANOVA analysis and percentage contributions of each factors such as cutting speed, feed rate, depth of cut and workpiece temperature are the significant hot machining process parameters affecting the multiple performance characteristics. In this study cutting speed is the most significant process parameter due to higher percentage contribution among the other parameters. From Table 3 the optimal process parameters are cutting speed (31 m/min) at level 1, feed rate (0.4mm/rev) at level 3, depth of cut (0.4 mm) at level 1, and workpiece temperature(400^0C) at level 2. Therefore experiment 7 in Table 3 fits the optimal process conditions.

Table 6 ANOVA table

Source	dof	Sum of squares	Mean square	F value	% contribution
A	2	37.4067	18.7033	38.56	46.42
B	2	24.3653	12.1826	25.11	30.23
C	2	9.8262	4.9131	10.13	12.19
D	2	0.2478	0.1239	0.26	0.3075
Error	18	8.7316	0.4851		
Total	26	80.5775			

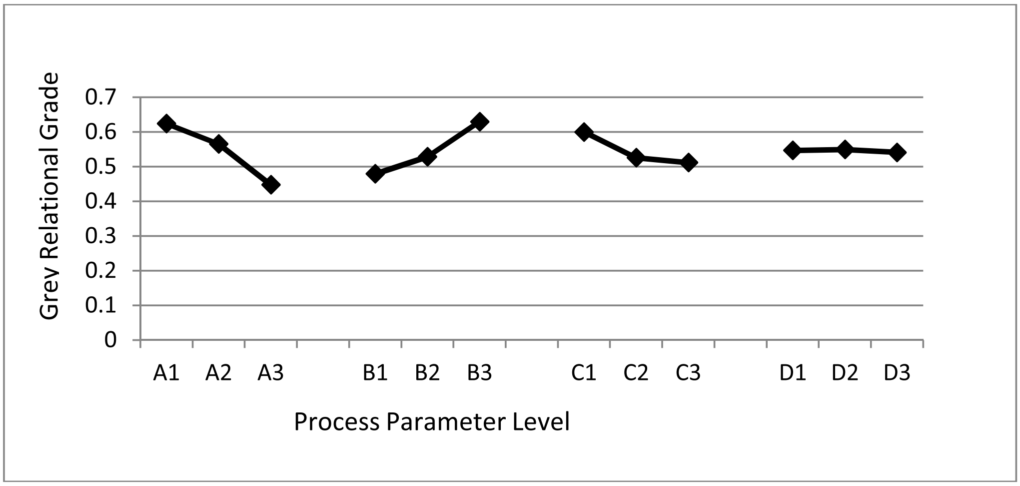

Fig. 2 Effect of hot machining parameters level on the grey grade.

3.4 Conformation tests.

The experimental results reveal that the optimal processes parameters are $A_1B_3C_1D_2$ (31 m/min, 0.4mm/rev, 0.4 mm, 400^0c) which was then employed to predict the grey relation that shows the hot machining of 15-5PH stainless steel. ANOVA analysis clearly shows that *A* (cutting speed),*B*(feed rate),*C*(depth of cut) can be classified as significant factors. Factor *D* (Workpiece temperature) is ignored in the calculation of grey relation prediction value of the optimal hot machining parameter combination due to its minimal effect. The factors which are more significant i.e, *A,B* and *C* are taken into consideration for the prediction of the grey relation $\alpha_{\text{predicted}}$ of the optimal hot machining parameters, and it can be calculated using the formula:

$$\alpha_{predicted} = \alpha_m + \sum_{i=1}^{N} (\alpha_0 - \alpha_m) \tag{11}$$

In which $\alpha_{\text{predicted}}$ is the grey relational grade for predicting the optimal hot machining parameters: α_0 is the average grey relational grade of the optimal level of a significant factor A, B, and C α_m the average grey relational grade: and N is the number of significant factors taken from ANOVA, which is 3.

Factor *D* (Workpiece temperature) is ignored in the calculation of grey relation prediction because factor D is insignificant. The effect of $A_1B_3C_1D_2$ is included. Calculation of grey relation grade for predicting the optimal hot machining parameters is as follows.

$$\alpha_{predicted} = \alpha_m + \sum_{i=1}^{3} (\alpha_0 - \alpha_m)$$

$$= 0.545 + (0.6235 - 0.545) + (0.6292 - 0.545) + (0.5995 - 0.545)$$

$$= 0.762$$

The confirmation experiment is conducted via the optimal hot machining parameter combination of $A_1B_3C_1D_2$ and was repeated three times. The calculated values for surface roughness and metal removal rate are respectively. The S/N ratio for the above three parameters were determined as 4.30 µm and 4.96 cm^3/min respectively. The S/N ratio of the above three parameters were determined as 12.02 and -13.19 respectively. The calculated value of grey relational grade is 0.757.

Comparison between initial and optimal hot machining process parameters are shown in Table 7. It is found that the use of optimal hot machining parameter combination enhances the grey relation of the single hot machining quality from 0.639 to 0.757 by 18.46%.

Table 7 *Comparison between initial and optimal process parameters*

level	Raw Data	Optimal hot machining parameters	
	$A_1B_3C_3D_2$	prediction $A_1B_3C_1D_2$	Experiment $A_1B_3C_1D_2$
Surface Roughness (µm)	2.58		4.30
Metal removal rate (cm^3/min)	3.78		4.96
Grey relation grade	0.639	0.762	0.757
Percentage of improvement of the grey relation grade = 18.46%			

4. Conclusion

Hence the following conclusions have been evaluated by applying the grey analysis on hot machining of 15-5PH stainless steel.

- The experimental results shows that cutting speed (31 m/min), feed rate (0.4mm/rev), depth of cut (0.4 mm), and workpiece temperature(400^{0}C) will give the optimal results for hot machining of 15-5PH stainless steel by using multi response optimization using grey relational analysis.
- From the ANOVA results reveal that cutting speed is has a most significant factor 46.42% in contribution ratio, While feed rate has 30.23% and depth of cut 12.19% influence on the surface roughness and metal removal rate in hot machining of 15-5PH stainless steel.
- Cutting speed, feed rate and depth of cut are the primary factors that affect the quality of hot machining of 15-5PH stainless steel, while workpiece temperature is considered as secondary factor.
- From the grey relation a significant improvement can be achieved by a combination of optimal hot machining parameters.

References

Alexandre Mondelin, F. Valiorgue, J. Rech, M. Coret, E.Feulvarch., 2012. Hybrid model for the prediction of residual stresses induced by 15-5PH steel turning. International journal of Mechanical sciences 58, 69-85.

Alexandre Mondelin, F. Valiorgue, J. Rech, M. Coret, E.Feulvarch., 2011. Surface integrity prediction in finish turning of 15-5PH stainless steel. 1st CIRP Conference on Surface Integrity (CSI) 19, 270-275.

A.Mondelin, F. Valiorgue, J. Rech, M. Coret, E.Feulvarch., 2013. Modelling of surface dynamic recrystallization during the finish turning of the 15-5PH steel, 14th CIRP conference on modelling of machining operations (CIRP CMMO) 8,311-315.

Aravindan S, Naveen Sait A, Noorul Haq A., 2008. A machinability study of GFRP pipes using statistical techniques. Int J Adv Manuf Technol 37:1069–1081

Ashok kumar, Y Balaji, N Eswara Prasad, G Gouda, K Tamilmani., 2013. Indegenous development and airworthiness certification of 15-5PH precipitation hardenable stainless steel for aircraft applications, Indian Academy of Sciences 3-23.

Bundell T.,1998.Taguchi methods. Proceeding of the 1998 European Conference on Taguchi Methods, Elsevier

Deng J., 1989. Introduction to grey system. J Grey Syst 1:1–24

D.K. Pal, S.K. Basu, 1971. Hot machining of austenitic manganese steel by shaping, *International Journal of Machine Tool Design Research*, Vol. 11, pp.45–61.

G Madhavulu, Basheer Ahmed, 1994. Hot Machining Process for improved Metal Removal Rates in turning operation , J. Mater. Process. Technol, 44.

Hinds, B.K. and Almeida, S.M.D., 1981. Plasma arc heating for hot machining, *International Journal of Machine Tool Design Research*, Vol. 21, pp.143–152.

Hsiao YF, Tarng YS, Huang WJ .,2010. Optimization of plasma arc welding parameters by using the Taguchi method with the grey relational analysis. Mater Manuf Process 23(1):51–58

K.P. Maitya, P.K. Swainb, 2008.An experimental investigation of hot-machining to predict tool life, journal of materials processing technology 198, 344–349.

Kunio Uehara, Hideo Takeshita.,1986.Cutting Ceramics with a Technique of Hot Machining. Annal CIRP, Vol. 32, 55–58.

Lopez de Lacalle, L.N., Sanchez, J.A., Lamikiz, A.Celaya, 2004. Plasma assisted milling of heat-resistant super alloys, Journal of Manufacturing Science & Engineering, Vol. 126, pp.274–285.

Lua HS, Changb CK, Hwanga NC, Chungc CT., 2009. Grey relational analysis coupled with principal component analysis for optimization design of the cutting parameters in high-speed end milling. J Mater Process Technol 209:3808–3817

L. Ozler, A. Inan, C. Ozel., 200. Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel, International Journal of Machine Tools & Manufacture.

N.N.S. Chen, K.C. Lo, 1974. Factors affecting tool life in hot machining of alloy steels, *International Journal of Machine Tool Design Research*, Vol. 14, pp.161–173.

Nihat Tosun, Latif Ozler, 2002. A study of tool life in hot machining using artificial neural networks and regression analysis method, Journal of Materials Processing Technology 124.

N. Tosun and L. Ozler, 2004. Optimization for hot turning operations with multiple performance characteristic, Int J Adv Manuf Technol .

Patel Pulak KM, Pandy M, Venkateswara Rao P., 2010. Optimisation of process parameters for multi-performance characteristics in EDMof Al_2O_3 ceramic composite. Int J Adv Manuf Technol 47:1137–1147

Pan LK, Wang CC, Wei SL, Sher HF., 2007. Optimizing multiple quality characteristics via Taguchi method-based grey analysis. J Mater Process Technol 182:107–116

Ragunath N, Pandey PM., 2007. Improving accuracy through shrinkage modeling by using Taguchi method in selective laser sintering. Int J Mach Tools Manuf 47:985–995

S Lei,Y.C. Shin, F.P. Incropera, 2001. Experimental investigation of thermo-mechanical characteristics in laser assisted machining of silicon nitride ceramics, *Journal of Manufacturing Science & Engineering*, Vol. 123, pp.639–646.

S.K. Thandra and S.K. Choudhury., 2010 Effect of cutting parameters on cutting force, surface finish and tool wear in hot machining, Int. J. Machining and Machinability of Materials, Vol. 7, Nos. ¾.

T.Kitagawa, K.Maekawa., 1990. Plasma Hot Machining for new Engineering materials. *Wear*, Vol. 139, pp.251–26

T.Kitagawa, . and K.Maekawa., 1988. Plasma hot machining for high hardness metals, *Bulletin of Japan Society of Precision Engineering*, Vol. 22, pp.145–151.

V. Raghuram, M.K. Muju., 1979. Improving tool life by magnetization in hot machining, *International Journal of Machine Tool Design Research*, Vol. 20, pp.87–96.